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ROBOT MANIPULATORS

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16. Abstract The general use of robot manipulators is explained and the basics of their design and operation are described for the average reader in this Znaniye -- series popular science booklet. Several pages of the first chapter include a discussion on the use of robot manipulators in space. Possibilities for fully and partially automatic robots, robot manipulator and "information" robots for space shuttles, space stations, and planetary exploration are outlined. The only example given of robots actually used in space is a mention of the Soviet "lunokhod," which is characterized as "the initial stage of planetary robot development." A short list of references is included.

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FOREWORD

Automation and technical progress are two inseparable concepts, since "the progress of technology is manifested in that human labor is increasingly replaced by machine labor[1]." There is practically no area of modern production in which further technical progress is possible without the broad utilization of automation equipment. /3*

Take for example machine building. The achievements in this area are well known. However today at most machine building enterprises equipment is divided as to types of machines or type of technology. This means that the technological process consists of a series of individual operations, the plant is thought of as a combination of different shops and divisions -- essentially, technologically independent units.

Automation quite basically changes the concept of the technological process in machine building, requiring a greater level of continuity in production, conversion of the plant into an integrated whole. In the solution of this problem, great significance is given to industrial robots, which can be used to combine various classes of operations, cementing the technological process, so to speak.

In this brochure, we study the class of robots most important for practical applications. These are the robot manipulators. In the future, it is already acknowledged, they will be of primary significance for various branches of the national economy.

The robot manipulator is a new technical system with manipulating devices and a more or less developed control system, /4 with a complex of sensing elements and, if necessary, some means of moving through space.

The manipulating devices of the robot are its actuating organs, imitating the actions of human arms in natural scale, or enlarged or reduced, as well as increased in strength if necessary.

The control system (with or without computer) may have several levels, similar to the various levels of the nervous system and brain of man which he uses to perform various manual

[1]V. I. Lenin, Complete Collected Works, Vol. 1, p. 78.

*Numbers in the margin indicate pagination in the foreign text.

operations; in simple cases, "without thinking," in more complex cases -- with recognition of objects and planning of his actions as a function of the situation and the task at hand.

The sensing elements of the robot, like human organs of sense, produce the necessary signals for the control system, informing it of the approach of the "hand" toward objects manipulated, of contact with the objects, of the location and configuration of the objects, and if necessary of their temperature, color, etc., including artificial vision and hearing, if necessary beyond the limits of human sensitivity (ultraviolet or infrared "colors," ultrasonic sound, etc.). These elements allow the robot to orient itself as necessary within the medium in which it functions.

The means for moving the robot may be whatever is needed depending on its purpose: walking mechanisms, devices on wheels, tracks or combinations of all three methods. Underwater work can be performed by swimming controlled apparatus. Their mobile base may also be flight vehicles of all types, including spacecraft. We can also imaging surface robots with small jet engines so that they can leap over obstacles, etc.

The control systems of robot manipulators are either completely automatic or involve the participation of a human operator (when complex operations must be performed).

The use of robot manipulators in the national economy is quite varied. They represent first of all the culmination of complex mechanization and automation of production processes. Here robots perform all sorts of manual operations in those /5
areas of the production line where manual operations are still used. This liberates man from the performance of monotonous, fatiguing, low-skill work, and expands the sphere of his creativity. The role of robot manipulators is also great in places where it is harmful or dangerous for man. Furthermore, the use of robot manipulators in many cases is expedient for the automation of stacking, loading and unloading, for the automation of construction and installation, oil well drilling and mine shaft digging and agricultural work. And, of course, open space, orbital stations, the moon and the unbreathable atmosphere of other planets.

Robots are also used in undersea space and on the floors of the seas and oceans for economic purposes, and for the study of the underwater world. Here, even at slight depths, it is ineffective, dangerous or simply impossible for man to work.

Another new technical system similar to robot manipulators consists of the so-called exoskeletons. They are intended to replace lost extremities in all of the details of their functioning. But this is not their only assignment. They also strengthen human arms and legs (an exoskeleton might be built into a special suit).

In this brochure, we will study the principles of construction of robot manipulators, their actuating organs, control systems and sensing systems, right down to the elements of artificial intellect. We show the basic, quite varied possibilities for practical application of robot manipulators in the national economy, their purpose and the operations they perform; we describe the contemporary status of this new area of science and technology and present the prospects for its development.

TABLE OF CONTENTS

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WHERE, WHEN AND HOW

Peculiarities of the Functioning of Robot Manipulators

We have witnessed the mechanization and automation of almost all types of manual labor and of many types of mental labor. Without these processes, human society as we know it today would be quite impossible.

Automation liberates man completely or partially from the function of controlling the operation of his machines. We can recall various automatic regulators, tracking systems, autopilots, automatic guidance devices, automatic machines for selling of tickets, newspapers, automatic machine tools, automated production lines, where man need only push the start button. However, in many cases the system even starts automatically in response to changes in the external situation. /6

There are also semiautomatic systems -- guidance, flight vehicle piloting and ship piloting, automated systems for the control of production processes, etc. Furthermore, automation is extending into the area of scientific experiments and testing of technology, to processes of planning of machines, instruments, electrical and electronic devices, to processes of planning and control of the national economy at various levels, to making organizational decisions based on analysis of the initial material and determination of possible results, etc. All in all, the possibilities for automation of manual and mental labor by means of digital computers seem unlimited.

In the light of all of this, let us define the tasks and position of robot manipulators in the overall system of mechanization and automation, as well as the basic peculiarities of their function.

An ordinary automaton is designed and constructed for repeated performance of a single operation. The nature of the operation may be quite various, discrete or continuous, simple or complex. What is essential is that it be rigidly designed for a definite operation, which is economically suitable with mass production, with no change in the operation throughout the service life of the automaton.

In contrast to such an automaton, a robot manipulator is a flexible, universal, multipurpose device. One robot can

perform a number of different operations. Even if each operation is performed by the robot according to a rigid program, it is possible rapidly to change the program to other operations which it is also capable of performing. However, it is also possible to construct robot manipulators with adaptation to the situation and with selftuning involving the necessary changes of operations, even if the moment for such a change cannot be rigidly programmed in advance. Robot manipulators also may /8
work in a semiautomatic mode, when a human, observing the actions of the robot, briefly takes over the controls when the situation becomes too complex for the robot.

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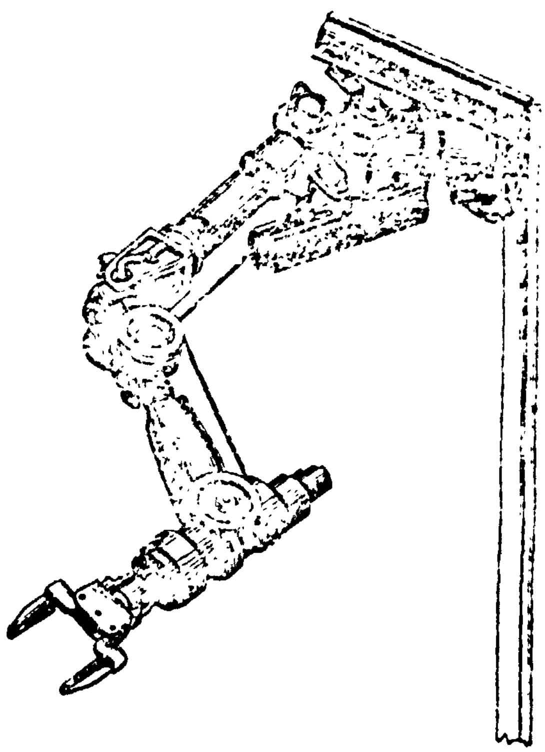

Figure 1. The Manipulator -- The Actuating Organ of a Robot

The universality of the operations of a robot manipulator is also a result of the fact that it has an actuating mechanism which imitates the human arm (Figure 1). The completeness of the imitation of the motions of the arm, i.e., the number of links and degrees of mobility, differs depending on the purpose of the robot. Furthermore, its motions may differ from the motions of the human arm, for example in that it not only rotates at the joints, but also moves forward and back. Furthermore, the length of certain elements may change (by means of telescopic devices). The hand is imitated by a clamp -- two-finger, three-finger or more. In the hand, in the clamp or in place of the clamp, various interchangeable tools can be placed (working and measuring devices), which the robot itself takes when required from special storage sockets, then replaces.

Thus, we repeat, the robot manipulator is a multipurpose machine which differs from an ordinary automaton in its flexibility and universality of performance of various operations. This also determines the area of its application, which will be described below in detail. We find that tasks suitable for robot manipulators are common in literally all areas of the national economy.

Modern automation systems usually consist of a closely interrelated complex of various technical devices. Therefore, the inclusion of a robot in such a system is frequently impossible or unsuitable without preliminary analysis of the operation of the entire system and, perhaps, certain changes.

The problem is that robots in general, including robot manipulators, do not simply improve various properties of the system by a certain percentage. They are capable of giving the system quite basically new qualities. Their application in many cases may make a basic change in organization of the system expedient, essentially increasing the effectiveness of the entire system. This type of question must be specially studied in each case when robot manipulators are used.

Of course, individual applications of robot manipulators, /9
not "tied in" with complex systems, are also possible.

In addition to robot manipulators, walking machines also have similar functioning principles and devices. They imitate the actions not of the arms, but rather of the legs of man and animals. Walking machines are quite promising for movement of various objects over terrain of arbitrary profile both on Earth and on other planets. Today, we can discuss most fully the operation of six-legged walking machines, although two-legged ones do also exist. The latter are significantly more complex from the standpoint of maintaining stability during motion.

Six-legged mechanisms, like insects, have many different gaits, i.e., sequences of movement of individual legs: some gaits are best at covering ground rapidly, others are more convenient for crossing irregular areas, etc.

Quite promising are combined wheeled-walking machines, which move by walking when rolling is impossible, then return to rolling. Another combination is that involving "jumping" over obstacles by means of special reaction engines.

However, any of these machines can, of course, carry robot manipulators as well. In general, the movement of robot manipulators on ordinary wheeled or tracked chassis is quite convenient for construction, warehouses, shops, etc.

Robot exoskeletons are also given great significance today. There are two areas for their use. The first -- medical -- area involves the restoration of the function of the extremities of a atient, or prosthesis. The second -- technical -- area involves increasing the strength of the extremities of a healthy person both by direct attachment of the mechanisms to them and by means of mechanisms built into a special suit. The functioning and structure are similar to those in the actuating arms of a robot manipulator, but there are significant differences.

Varieties of Robot Manipulators

Let us first study the basic varieties of robot manipulators on the large scale, not according to their purpose (more about this later), but rather according to their principles of design, primarily their principles of control and sensing. We /10
can present a common functional diagram for the control system of robot manipulators, applicable to all types (Figure 2). Various numbers of the boxes and connections on this diagram will be present in various classes of robots.

Box 1 represents the environment, in which the actuating organs of the robot must work. It includes also the objects in the environment which the robot must manipulate or which it must avoid as obstacles as its actuating organs move.

The actuating organs (Box 2) of the robot are its "arms." Mechanical movement of the elements of the arms of the robot with all degrees of mobility is performed by the system of drives (Box 3) and the drive control unit (Box 4). We have in mind here only the lowest degree of the control system controlling the movement of the drives as tracking systems with internal correcting devices. The diagram illustrates the connections between these three units (direct and feedback) by arrows.

This set of boxes (2, 3, 4) forms the manipulator. The manipulator (or several manipulators) is the basic actuating portion of the robot.

When there are means for moving the body of the robot, these also must have their own drive system or motor, with the corresponding motor control devices.

As we have stated, the robot may be either fully automated, or may work with a human operator. Automatically controlled robots are divided into three groups, corresponding to the his-torical sequence of their development. However, this do[illegible] mean that the first type was replaced by the second, th[illegible] second by the third. On the contrary, all classes and [illegible] of robot manipulators, from the most simple to the most [illegible] retain their position, each with its own area of applica[illegible] /11

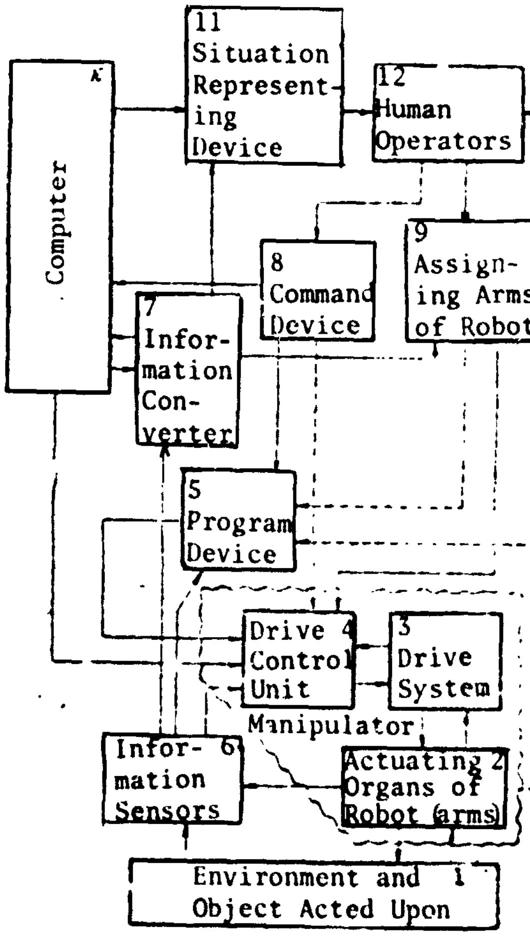

Figure 2. General Functional Diagram of Various Types of Robot Manipulators

The first variety of robots consists of the simple manipu-lator (Boxes 2, 3, 4 on Figure 2) with a programmed control device (Box 5). This sort of robot performs a set of rigidly programmed operations. For this to be possible, the environment in which it exists must be fully known in advance and organized /12 in a certain way, and the objects which it manipulates must be found in a given initial position, strictly oriented in space.

The programming device may be easy to adjust to the per-formance of another complex of operations, but these must also be strictly organized. A series of programs can be placed in the programming device in advance, although each new program may also be put in operation by "teaching" the robot. For example, a human might, roughly speaking, take the robot by the "hand" and show it the entire complex of operations required. The complex is recorded (memorized) in the programming device, after which the robot automatically repeats the cycle. However, it is not at all necessary that the human operator actually guide the hand of the robot's arm to do this programming. It can be done from the control panel by pressing buttons corresponding to the various degrees of mobility of the robot. Other assigning organs may also be used, which we will study below.

This first variety includes many industrial robots in use at the present time.

The second variety includes robots with feeling. What do we mean by feeling? The actuating arms of the robot are equipped with various sensors which output information on the status of the arms themselves and of the objects which they are to manipulate, as well as the basic necessary properties of the environment in which the process is performed. These sensors might be tactile sensors, signaling contact of the robot's arm with the objects; location sensors, determining the speed of motion and distance to certain objects; television or optical sensors, providing artificial vision; sensors measuring forces and torque on the actuating arms of the robot during performance of operations, as well as sensors differentiating color, temperature, sounds, etc.

The system of sensors (Box 6 in Figure 2) serves as a source of feedback to control the actions of the robot. Namely, the signals of the sensors are converted as necessary (Box 7) and processed in a digital computer (Box 10) or simpler logic devices (Box 5) in order to form control signals which are fed to the drive systems of the actuating arms (4, 3, 2). As a result, the robot begins to act in consideration of the actual situation around it. In other words, it can adapt (modify its /13
actions) to the actual situation. It now has organs of sense. Depending on the number and type of sensors, various versions of feeling are created, according to the tasks of the robots in the various environments.

In contrast to the first variety, robots with feeling can operate in an incompletely defined and continually changing environment. The control computer contains programs for typical operations which themselves are automatically brought into play, in a predetermined sequence, depending on the situation.

The third variety is robots with artificial intellect (also called "integrated robots"). These machines have a very high degree of "feeling" -- devices for perception and recognition of patterns (situations), devices for making decisions and automatic planning and testing of operations depending on the goals at hand and the situation recognized.

There are various ways to give a robot various elements of artificial intellect. The structure and quality of such systems are determined on the one hand by the content and complexity of the tasks and on the other hand by the technical capabilities for realization of the required elements of artificial intellect.

The control systems of robot manipulators of this third variety have a complex hierarchical structure, i.e., several levels. The lowest level is the actual control of the drives of the actuating organs (movement of the arms of the manipulator and, if necessary, of the body). The next level is the formation of control signals for these drives. This is followed by programming of details of the operation. Still higher is the level of planning of the complex of operations as a part of the larger plan, etc. Each level of the control system generally has its own feedback from various information sensors.

We have described the class of fully automatic robot manipulators. Let us now go over to another class -- robot manipulators whose control systems include a human operator. /14
These are the so-called bioengineering control systems: actions of a human operator are combined in various ways with the operation of automatic equipment in the processes of control and information processing.

The first variety of this class of systems includes the copying manipulators (usually with remote control). A manipulator is called a copying manipulator when there is an assigning organ similar to the actuating organ, generally with a change of scale of geometric dimensions and forces (Box 9 in Figure 2). It may be located at any distance from the actuating arm. The human operator holds the assigning organ in his own arms and moves it as required to supply control signals which are transmitted to the actuating arm of the manipulator. The arm performs the necessary operations, precisely copying all motions of the assigning organ.

Such copying manipulators are most frequently used to work under extreme conditions. The actuating arms of the manipulator are placed in the medium with these extreme conditions, while the human operator and the assigning organ is located in a separate room.

There must be visual feedback between the object acted upon by the manipulator and the human operator, perhaps directly through a window, perhaps by means of optical devices or a television image (Box 11).

If additional feedback to the asigning organ is also used, the effectiveness of the operator significantly increases (due to the fact that he can feel the working forces and moments). This increases the degree of participation of man in the direct performance of the operation at the working location. Such systems are called two-way copying manipulators.

Copying manipulators utilize the intellect of the human operator. They can be used to perform precise and complex operations in an uncertain, changing situation. True, the time of performance of each operation under extreme conditions using a copying manipulator is significantly greater than if the human operator performed the same operation with his own hands under normal conditions. /15

Copying manipulators have been used for many years to work in sealed chambers with radioactive substances. Recently, they have also been used for underwater work at all depths in the seas and oceans, and also in space and in corrosive media.

However, the purely copying mode is not always desirable, since in this case the human operator must continually track all details of the operation with his own arms, and is sensible only for complex, nonstandard actions. But if an operation of this type alternates with simpler, repeated actions, it is expedient to program the latter operations. Then the human operator simply switches on various programs for operation in the automatic mode and takes control himself only from time to time.

This type of combined man-machine control of robots can be performed in a wide variety of versions. We noted above the simple combination of alternating automatic programming and manual copying modes of control of the robot manipulator. Similar combined control is also possible when working with sensing robots, when the robot performs operations with a certain degree of adaptation to the external situation. The human operator here more frequently acts as an observer and less frequently takes control himself, when the specifics of the operation go beyond the capabilities (qualifications) of the robot.

We note that the control of the actions of a robot manipulator by a man need not be in the copying mode. The command mode is also possible, in which the human operator controls the robot by pressing buttons or moving a control lever (with slight displacements of the controls).

The button mode is not very effective at present, while command control by a lever is of greater interest. In the general case, a lever can be made with all six degrees of freedom in space, but with slight movement required in any direction. The human operator, by pressing on the lever, controls the movement of the end of the actuating arm (i.e., the clamp), both linear and angular: by pressing on the spring support of the lever harder or softer, the speed or force of the movement of the clamp can be assigned. /16

Simpler control levers, with three degrees of freedom, are also used. Using one lever, the operator might assign the forward and backward motion, while another lever is used to assign the angular movement of the clamp. Other versions are also possible.

Since the operator here assigns only the movement of the clamp, there must be an automatic link between the command lever and the actuating arm of the robot, which develops signals to control the drive units in each hinge of the actuating arm in response to the general command, so that the required motion is performed. If a computer is included in the automatic control circuit, it can perform these functions in response to commands from the lever.

Let us now discuss the adjustment of automatic robots with programmed control to new operating cycles. This readjustment (learning) is performed by a human by means of assigning organs similar to the arms or by means of buttoned command structures, or by a control lever of one of the types just described. All motions (control signals) are recorded as a program. The robot, thus taught, can independently perform the entire cycle of operations and repeat it as many times as necessary.

Finally, for automatic robots with feeling and elements of artificial intellect, the human operator can participate in the control process in the so-called supervisor mode. This means that all of the details of the operation and even certain cycles of operations are generated independently by the robot. However, the human, when necessary, may interfere in the control process at the higher levels of planning of operations and give the robot instructions on the large scale.

Application of Robot Manipulators in Industry and Construction

Industrial robots are presently most widely used. As yet, robot manipulators are used in practice with programmed control, but feeling robots are now beginning to appear.

There are many varieties of industrial robots both in the Soviet Union and in the USA, Japan and other countries. Their manipulators have from three to nine degrees of mobility, with /17 various designs of clamps and tools (including automatically interchangeable tools). The methods of programming also differ, but in all cases they allow rather rapid adjustment to a new cycle of operations within the limits of the capabilities of each robot.

Industrial robots perform, first of all, manual operations instead of man in all those areas of industrial production in which they have not yet been successfully automated. Thus, overall combined automation of production is achieved, which is economically quite effective and increases productivity as a whole.

Secondly, industrial robots can be successfully used in place of ordinary automata wherever a varied list of products must be produced with comparatively frequent changes of production cycle. Under these conditions, one industrial robot can service the process of manufacture of a number of different products, rapidly switching from one to the other, whereas automata would have to be purchased in larger numbers and many of them would be insufficiently used. The high economic effectiveness here also is obvious.

Thirdly, there are many manual operations which workers must perform under harmful conditions. In all these cases, the question is not so much of economic effectiveness as of the possibility in principle of performing production operations without high risk to the health and life of humans.

In connection with this last factor, under such extreme production conditions it is necessary not only to use industrial robots with programmed control, but also copying manipulators with remote control by man.

Let us present a few examples of operations performed by industrial robots.

In processing parts on metal cutting machine tools, the robot picks up an arriving part and places it as required in the machine. While it is being worked, the robot takes a part which has been processed on another machine and places it on the next machine. The robot's arm then returns to the first machine, /18
removes the first part, then places the next arriving part on the first machine, etc. Thus, without fatigue and very rhythmically, the robot performs the manual operations of two or three workers.

A robot operates similarly at a stamping press, placing a blank in the first press and moving parts from press to press. The same thing occurs during heat treatment of parts in combination, let us say, with grinding.

Other classes of operations occur during welding operations, painting of various surfaces, etc. when the robot participates directly in the technological process.

Industrial robots are broadly used in stamping, pressing and foundry work, where their high productivity and rhythmicity, in comparison with man are not reduced by fatigue due to the heavy work, or by the poor working conditions.

Robot manipulators are quite significant for conveyor processes, freeing man from boring, fatiguing operations. Elementary operations are performed -- parts are placed in their assigned position, screwed together or attached by spot welding or riveting, stamped plates attached and much more.

Most interesting from the standpoint of the variety and quality of operations is the use of robots for conveyorless assembly of units, instruments and machines. This requires the most complete universality of the robot and the most complex programs for their functioning (Figure 3).

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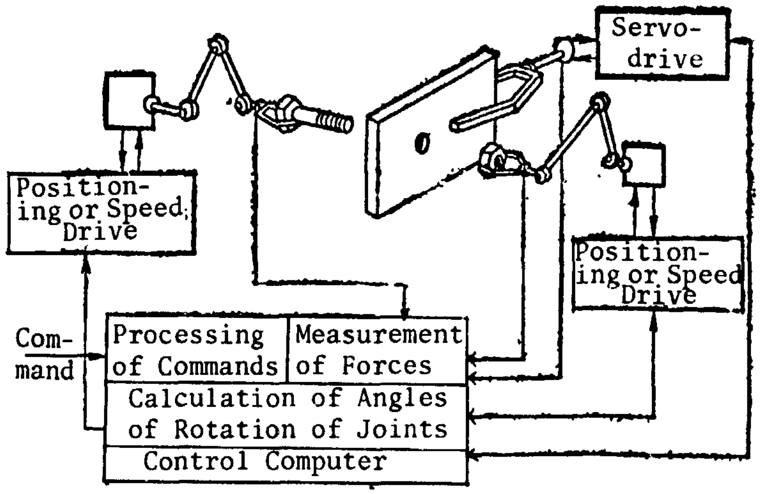

Figure 3. Diagram of an Assembly Process

A separate class consists of robots designed for operations involving the miniaturized objects of modern electronics, with their processing, coating, soldering, testing, checking and assembly.

Robots performing supplementary operations are already in use in production.

As we have stated, under harmful or dangerous production conditions, copying manipulators are also used, when a human, in a safe place, remotely controls the operations of the actuating arms of the manipulator. This is particularly true of the nuclear industry. Since there is no other way to perform these /20 operations, copying manipulators appeared with the very birth of this industry. Their experience then began to be extended to other types of harmful production processes, with which man must deal with increasing frequency as science and technology develop.

The use of robots in industrial production has not been limited to the areas we have discussed. There are many other manual operations, involving the transportation of materials, tools and parts from the point of storage to the working location. These operations can also be programmed completely or partially, performed upon request (button call) from each working position or a common control panel. They can be performed by robots which move around the shop, for example on rails built into the floor or walls.

The same thing is also true of the operations of warehousing of materials, tools, parts and units both from the working positions in the shop and arriving from outside the shop.

The use of robots in the chemical, textile and food industries has certain specific features.

Furthermore, robots in all branches can perform measuring, testing and various information functions, included in an overall automated production control system.

Generally, in most cases, industrial robots are not machines which have been specially developed. Their activity can be closely related in a single system with all other automation devices, mechanisms and equipment.

Therefore, first of all, the use of robots may require new planning of a number of technological operations. Secondly, the cooperation of several robots with each other may be required.

When a production process is controlled by a computer, it may also control a family of robots, in combination with other equipment. In addition to the central computer, small control computers are used at the locations where the robots work. On this basis, a transition can be made to the use of feeling industrial robots, then to robots with elements of artificial intelligence.

Let us now discuss robot builders. Construction has been significantly mechanized and in its style is approaching industrial processes. The production of construction materials, parts and units of buildings is being increasingly automated and is becoming an industrial process. Therefore, the use of robots as important new elements in the improvement of the overall mechanization and automation of the construction materials industry and in building-construction combines is equally important. /21

During construction, in installation work, including the installation of equipment in production buildings and power engineering structures under construction, involves a great deal of manual labor in supplementary and even in primary operations. For some of these processes, it is not suitable to produce automata; more universal, easily readjusted devices such as robots with programmed control are required. Robots may be simple in design for simple moving an installation operations, or more complex for more complex work.

In other words, the use of robot manipulators may be profitable if we do not attempt to produce a single universal robot, but rather create a number of specialized robots for each class of manual operations. Each type should have the maximum possible simplicity and the minimum possible cost, but should be to some extent universal and capable of rapid adjustment to any operation within its class. This is the most important thing.

Here it is possible to use not only automatic robots with programmed control, but even remotely controlled manipulators in the copying or command mode for nonstandard high, underground and other operations.

A certain portion of manual operations in construction and installation work consists of loading and unloading operations and storage, sorting and checking of materials and units, where specialized robot manipulators are also useful.

Thus, industrial production and construction and installation work are the primary areas of application of robot manipulators of all classes and varieties. However, we must also discuss the prospects for the application of robot manipulators in the mining, petroleum and gas industries as well. The con- /22
ceptual and technical-economic basis of their application is the same. However, of course, there are certain specifics of the concrete operations which should be assigned to these robots.

Apparently, a number of agricultural operations, based on the experience of application of industrial robots, will later also be automated by specialized agricultural robot manipulators.

We can now speak of the usefulness of creating domestic robots, particularly robots in the rich and varied sphere of servicing the population. Here also, many manual operations are not suitable for performance by automata. More universal, multipurpose and adaptable devices are required.

However, in addition to the purely economic factors, there are also social factors. The fact is that robot manipulators liberate a mass of workers from the performance of unskilled, monotonous, boring and fatiguing manual operations everywhere, including on the conveyor. Robots liberate them for more intellectual labor -- the control of machines, test observation, investigation, adjustment, etc. People create robots so that, so to speak, they themselves will not be converted into robots as production develops. This is particularly true of production operations under abnormal conditions -- unhealthy and dangerous situations.

One important fact is that as the general cultural level of the population increases, it is already becoming difficult to find workers for unskilled manual operations. The workers, when they undertake such work, do not stay there for long. This social problem can be solved only by broad application of robot manipulators.

Today's level of technology and capabilities of industry are such that the creation of various robot manipulators and their series production are quite realistic (at least automatic robots with programmed control and manipulators with copying and command control, as well as robots with combined man-machine control).

Underwater and Space Robot Manipulators

The mastery of the world ocean is a subject of great study in all the developed countries of the world. The floor of the seas and oceans is rich in mineral resources. The entire mass of water, down to the greatest depths, contains valuable food and medicinal substances. Some countries have already begun mining underwater minerals, while others are prepared to begin such work in the immediate future, to say nothing of the continuous expansion of the fishing industry and the extraction of other biological objects, already long a subject of human endeavor, as well as the recovery of pearls, coral, etc. /23

The organization of human activity in the seas and oceans (both on the surface and particularly at great depths) on an industrial basis is impossible without the broadest application of all varieties of robots, particularly information robots and robot manipulators. This results from the need to automate information processes and mechanize manual operations on the one hand, and from the fact that the direct performance of manual operations by man under water, even at slight depths, is ineffective and frequently dangerous, while at great depths it is simply impossible. This fact, if we consider the specifics of the underwater medium and the great mass of uncertainties in the situation and in the objects of man's activity at great depths, leads us to conclude that the tasks which must be performed by underwater robot manipulators will be quite difficult.

Therefore, in contrast to industry, the automatic robot manipulator with programmed control can be significantly less frequently used here. Most typical for underwater conditions are robot manipulators in which the control system involves the participation of a human operator in some form. For the time being, in most cases copying manipulators are used in underwater situations. It is quite important here to use copying manipulators of two-way type, to increase the effectiveness of the work of the human operator.

In the future, combined man-machine control systems with various degrees of automation depending on the operations performed will be most common. The independent portion of the actions of the robot in automatic modes underwater will gradually increase (with the development of sensing technology and /24 the use of computers). In individual cases, of course, the use of fully automatic robots may be possible.

In addition to the industrial mastery of the mineral, energy and food resources of the seas and oceans, very important is comprehensive fundamental study of the underwater environment at all depths and on the sea floor. Without this, we cannot organize any mastery by man of such an as yet inaccessible environment. Scientific oceanographic studies, hydrological and hydrobiological research today represent tremendous difficulties, and robots and robot manipulators must play a primary role in overcoming them.

Another important area of application of underwater robot manipulators is in emergency rescue work, the raising of objects from various depths, inspection and repair operations on the underwater portions of ships, submarine cable lines and pipelines and other types of underwater engineering work, including the installation of many underwater structures which will be required in the further mastery of the seas and oceans.

We have described on the broad scale the areas of application of underwater robots. We can present a few examples of specific operations. During lifting operations these include the attachment of cables to the object to be raised from the depths. During repair operations these include underwater welding, cutting, riveting and painting. During underwater installation these include hoisting and transport operations, connection of individual parts. During research activity these include the collection of mineral and biological specimens, drilling of the floor. In the fishing industry these include the recovery of snagged or lost nets. In other cases these include disarming of mines or other armament, laying of underwater communications lines and pipelines, installation of underwater hydroacoustical stations; manipulation of radioactive substances and devices, particularly in marine nuclear power plants;

performance of manual operations in emergency situations, and much more.

To perform such a great variety of activities, robot manipulators must have controllable means of moving under the water. Of course, versions of stationary operation are also possible, /25
but in most cases underwater robots will deal with floating objects.

Obviously, in comparison to ordinary industrial robot manipulators, underwater robot manipulators have a number of specific peculiarities (in addition to the specifics of the control principles we have already mentioned). Of primary significance is the high hydrostatic pressure under the water, creating additional forces and moments both in the form of the continuous load and resistance to motion, and that generated by the seals in the watertight sealing system. Hydrodynamic factors also play a certain role as the elements of the manipulator arm move through the water.

One specific property of the underwater medium is poor visibility, made worse by silt stirred up from the bottom. This represents a very unfavorable factor for observation of the course of an operation as one attempts to control it. Particularly difficult in this respect is remote control when observation is performed by television.

Great difficulties also arise due to the fact that ordinary radio waves do not propagate through the water. True, communications and location can be organized using the hydroacoustical principle, but one must frequently use wires for communications, which is a very complex and cumbersome task. Cables hinder movement, problems of assuring sufficient cable strength while minimizing weight arise, the signal transmission channels must be compressed to the maximum in both directions (command and information channels, including television channels), etc.

Hoisting lines are frequently used for emergency recovery of apparatus, particularly if men are inside. The problems here are the same as for communications cables: their functions can be combined into a single cable line.

Under certain conditions, wireless communications using special bouys floating on the surface can be used, the bouys transforming hydroacoustical information transmitted through the water into radio signals.

As in industry, it is possible here to combine robots into a system with central and peripheral computers controlled from a single point. Such a system can service an entire complex of underwater research or engineering operations.

Under those conditions when the controlled underwater apparatus carries a robot manipulator, plus an information robot /26 as its basic equipment, the apparatus can be called an underwater robot, since its body, movement and stabilization system are actually means for moving the robot.

On large submarine or surface vessels, robot manipulators must be considered individual technical devices. For example, they can move over the outer surface of the hull of a ship or submarine, performing operations at various locations. They may even temporarily separate from the ship then return to it.

In general, the prospects for development and utilization of underwater robots are great; progress in the solution of most of the most important problems of mastery of the seas and oceans is unthinkable without them.

Space, in comparison to the underwater medium, is the other extreme of extreme parameters (as concerns pressure and density). We should differentiate the conditions of functioning of robots in open space and on the moon (where there is no atmosphere), on the one hand, from conditions in the atmosphere and on the surface of Mars, Venus and the other planets.

In open space and on the moon, we must deal with the vacuum, with significant radiation, sharp changes in temperature, the absence or marked reduction of the force of gravity and the unique surface of the moon. As concerns the planets, each of them has greatly differing peculiarities both as to temperature, composition and density of the atmosphere, and as concerns properties of the surface.

What is the significance of this? All of this affects the technical decisions which must be made in the creation of space manipulators of various types.

In space, as under water, the participation of man in the control of the robot is great (copying manipulators and combined man-machine control systems). Of course, a certain portion of the operations in space can be performed by robots fully independently in the automatic mode.

Of particular significance is the movement of robots, automatic or controlled by man, over the surface of the moon and the planets. The transportation devices must allow the robot to move over the terrain no matter what its shape and no matter what its soil type. One successful version of such a /27 device is known to all -- the Soviet lunokhod. Other methods are also possible: walking mechanisms, combined rolling and walking mechanisms, movement by jumps, with reaction engines, etc.

Both robot manipulators and information robots will operate in space and on the planets. Here, as in the ocean, it is of identical importance to perform various technical operations and to study the environment and situation. An example of such operations is the repair of solar batteries, antennas and other devices outside the hull of a spacecraft; the changing of film cassettes in cameras, etc. Outside work might also involve welding or cutting in a vacuum. These operations, along with others, will occur in the assembly of large orbital space stations of parts individually placed in orbit. Here the robots will also perform installation of various apparatus, power and electronic devices, etc.

Robots can help in the docking and undocking of spacecraft or individual units, in the refueling of spacecraft, in the performance of other types of servicing. These operations are particularly important for space shuttles, performing trips between the Earth and orbital sp stations.

Frequently, it will be necessary to manipulate scientific instruments outside the body or in special compartments of spacecraft; this also requires the creation of devices with several degrees of mobility of the arms of the robot, with the corresponding control system.

Obviously, most operations on the surface of the moon and the planets must be performed by robots, since there is no sense in risking human life for these purposes. Manned flight to these places is justified only for the solution of the most important and basic problems, when observations requiring human intellect must be performed. Both fully automatic robots and semiautomatic robots including human operators on Earth in the control system, or, under exceptional conditions in the device moving over the surface of the planet, can be used on the moon and the planets. A human operator on Earth must have an image of the situation in the region where the robot is /28 working (for example, a television image), plus a command radio link. The significant delay in both the television image and in the performance of commands resulting from the propagation delay of radio signals in both directions must be considered. This time is measured in seconds for the moon, in minutes for the planets. This delay, even with ideal work by the operator and the actuating devices, makes the details of the control process significantly more difficult.

The Soviet lunokhods were the initial stage in the development of planetary robots of both information and manipulation type. They contained simple arms, they took soil samples, they automatically performed various studies, transmitting the information back to Earth.

Robots on the moon and planets can not only take soil and rock samples, but also install and assemble structures carrying apparatus and service the landing and takeoff of spacecraft delivering various payloads to the planets, and can perform the required unloading and transport operations on the planet.

In this chapter we have studied only the general problems of functioning and utilization of various types of robot manipulators. In subsequent chapters we will describe their design and give an idea of the main stages involved in the planning of robot manipulators and their control systems.

ACTUATING ORGANS

The Actuating Arms of a Robot

The arms of a robot, like the arms of a human, have many degrees of freedom of mobility. However, there is no need precisely to copy the human arm. Some degrees of mobility of the human arm are usually not reproduced, for example the many joints of the fingers. Others may be made differently, while still others are introduced anew, for example telesopic elongation of individual elements of the arm or reciprocating movement away from the body of the robot.

Depending on the nature of the operations performed, the number of degrees of mobility of the arm varies from 3 to 12. /29
The most widely used arms in practice at the present time have 4 to 7. In various types of robot arms with the same number of degrees of freedom, a different selection may be used, for example only rotational or with reciprocating motion as well, with both types distributed differently among the elements of the arm. Consequently, a very large number of versions of kinematic plans of the actuating arms of robots is possible.

Figure 4 shows two versions of the kinematic plan of a mechanical robot arm, each with 12 degrees of mobility. In both versions (by analogy with a human arm), hinge 5 corresponds to rotation in the elbow, 7 and 8 to 2 degrees of rotation of the hand, 6 to the rotation of the hand relative to the elbow (rotation of the forearm), 9 to the rotation of the clamp, 10 to opening of the clamp, 4 to rotation of the elbow relative to the shoulder joint (rotation of the shoulder), 2 and 3 to 2 degrees of rotation in the shoulder joint, 1 to reciprocating movement (extension) of the entire arm from the body of the robot together with the shoulder joint (a motion which is not possible in the human shoulder).

These 10 movements are identical in both versions. The differ in that in the first version 11 and 12 are rotations of the lower portions of the clamp jaws (finger joints), while in the second 11 and 12 represent rotation similar to the rotation of the body of a seated man.

Figure 5 shows three versions of the kinematic plan of an actuating arm with 9 degrees of freedom. Here 1 and 2 are rotations in the attached shoulder joint, 4 in the elbow joint. The various versions can be seen from the diagrams. We note only that in the diagram in the middle of the picture, the rotation of the lower portions of the jaws of the clamp have 1 degree of mobility 9, on the assumption that they both rotate simultaneously by the same angle (their movements are rigidly connected).

In addition to the differences in distribution of degrees of mobility along the arm of the robot, the differences in the relationship of geometric dimensions of the individual elements are also significant.

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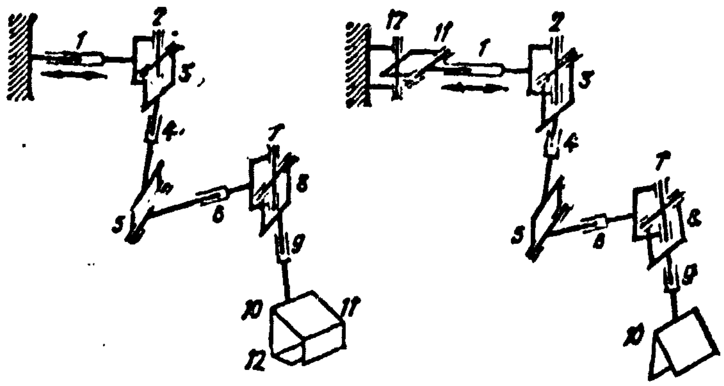

Figure 4. Kinematic Diagrams of the Arm of a Robot with 12 Degrees of Mobility

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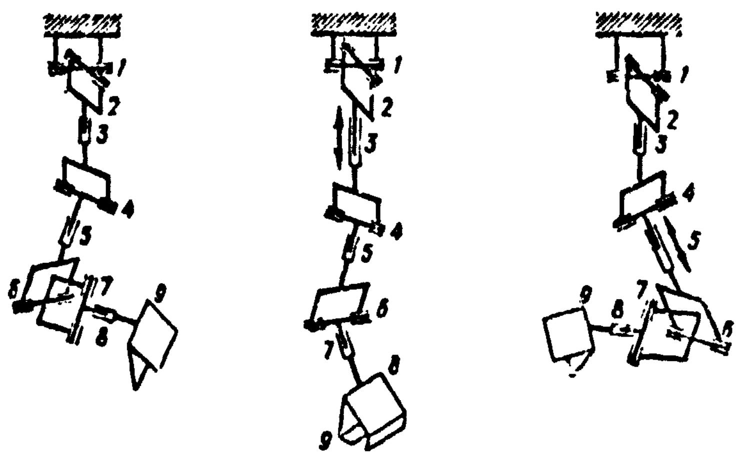

Figure 5. Kinematic Diagrams of the Arm of a Robot with 9 Degrees of Mobility

The selection of any given version of kinematic plan is determined by a number of specific conditions and requirements. /32 First of all, it must assure a sufficient degree of universality of the functioning of the robot in relationship to the cycles of operations in the environment in which it works; secondly, the plan must provide the greatest possible simplicity of design of the arm, ease of manufacture and minimum cost. These are the basic requirements, which then break down into a number of specific requirements, to which others are added, depending on the area of application of the system. First of all, the kinematic system of the arm must guarantee that the clamp can be moved to any point in the assigned working zone of the robot; furthermore, any necessary angular orientation of the clamp must be possible at all points. In the general case, this requires 6 degrees of freedom of motion of the clamp (as a solid body, not considering the motion of its jaws, which is a separate problem). Let us represent this number by m. In many particular problems, $m \leq 6$, i.e., 5, 4 or sometimes even only 3 degrees of freedom are required (for example, in the simple Japanese industrial robot "Aida" one vertical motion, one horizontal motion and one rotation of the clamp around its horizontal axis).

Obviously, in order to realize the assigned number m of degrees of freedom of motion of the clamp, the arm itself must have number of degrees of freedom n no less than m, to which we can add the number k of degrees of motion of the clamp. Consequently, considering this, $n \geq m + k$ (the number of k is frequently equal to 1 but, generally speaking, may also be greater).

Each assigned number of degrees of mobility of the arm can correspond, as we know, to various versions of the kinematic plan. This means that the designer can select any given version so as to satisfy simultaneously a number of other requirements. For example: the change of angular orientation of the clamp with its position at any point in the working zone must not involve significant movements of links in the arm far from the clamp. What determines this? The distribution of degrees of mobility with a fixed total number.

In order to maintain the necessary maneuverability of the robot arm (for example if there are obstacles in the working zone, if it must reach into difficultly accessible places), the /33
number of degrees of mobility of the arm n must be greater than m. Then the clamp can be put into a given position in space with various configurations of the mutual placement of the elements of the arm, which is required to reach around various obstacles. This brings up the practical need of seven, nine or even more degrees of mobility, in spite of the trend toward limitation to the minimum number (Figure 6).

Of course, all degrees of mobility of such an arm must be controllable, must not shift involuntarily under the influence of external forces (particularly, weight, hydrodynamic forces, etc.), which can occur in principle even with unchanged clamp position. As concerns the undesirable influence of the forces of the weight of the elements themselves, there are special methods for balancing them.

Analysis and synthesis of the kinematic diagram of an actuating arm considering the complex of conditions and requirements in a difficult task. The problem is that one must analyze the arbitrary three-dimensional movement of a multiple-element mechanism with many degrees of freedom. There are various approaches to the solution of this problem. Based on them, engineering methods can be developed for kinematic analysis and synthesis of actuating arms for various areas of application.

In complex cases, calculations should be automated, using machine methods of planning such as graphic displays controlled by a digital computer. The designer observes a moving image of the kinematic system which he is synthesizing on the screen and can correct and improve it as he observes. This type of projection allows, first of all, consideration of all of the fine points of the three-dimensional kinematics of the multiple-element arm and, secondly, reduction of the time required in the preliminary stages of experimental modeling.

This same method, considering the speeds and accelerations involved, can be used to represent a picture of the distribution of static and dynamic forces and moments along the arm.

Let us now go over to a description of the dynamics of an actuating robot arm.

The dynamic equations of motion of a multiple-element arm are still more complex than the kinematic equations. They /35 include the complexities of nonlinear spatial kinematics plus the force factors and dynamic terms.

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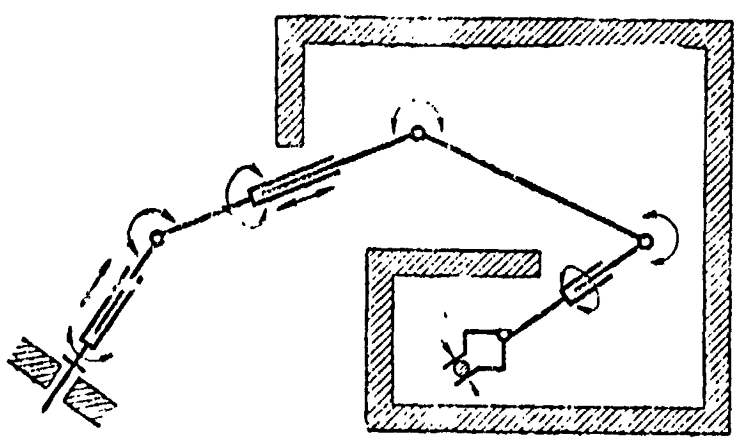

Figure 6. Diagram of Avoidance of Obstacles

Each degree of mobility, if we consider the elements of the arm absolutely rigid, corresponds to a second order dynamic equation. The overall order of the system is increased still further if we consider the elasticity of the elements. All of the equations of the elements are interrelated and studied together. The interrelationships are quite complex if we consider their arbitrary spatial distribution.

Actually, when the motion of the first element of the arm (shoulder) is analyzed, it amounts to simple rotation about a nonmoving point or a nonmoving axis. However, we must consider that the first element carries the entire arm. Consequently, the moments of inertia in the equation for the first element will be essentially variable, depending on the total change in configuration of the arm in the process of movement of all elements. In other words, they depend on the instantaneous coordinates of all moving elements, which determines the dynamic interconnection of all degrees of mobility.

For the last element of the arm (hand), in contrast, the expressions of the moments of inertia will be simpler, but the equation of motion is more complex. The problem is that the point of attachment of the last link is movable, and its motion in space is determined by the combined motion of all preceding elements. Consequently, here also the dynamic interrelationship of all degrees of mobility is complex, but expressed in a different form.

The equations of motion of intermediate elements of the arm between the first and the last will be complex due to both of these factors of dynamic interrelationship.

Furthermore, the expressions for forces and moments acting in the hinges of each individual element are equally complex, since they depend not only on the load at the end of the arm and other external forces, but also on the corresponding distances (arms of action of forces). These will vary due to the significant changes in overall configuration of the arm as it moves, i.e., also depend on the instantaneous coordinates of all elements).

Finally, we must also consider such factors as dry and viscous friction in the hinges, clearances in mechanical drives, elasticity of mechanical links, etc. This also complicates the system of equations of motion of the actuating arm. /36

A knowledge of the dynamic equations of motion of an arm of a robot is necessary for intelligent planning of the control system of the arm; an arm with many degrees of mobility is in this case an object of control. Each hinge in the arm has its own drive, and various control signals must be sent to each drive.

Since it is very difficult to deal with the full system of equations of three-dimensional motion of the entire arm at once, the main control circuits are first constructed individually for each element (each hinge). Then the interconnections of the degrees of mobility are analyzed and the corresponding corrections introduced. Finally, once we have the full system of dynamic equations of three-dimensional motion, we make the final arrangement and work out the entire organization of control.

We should also discuss the clamp at the end of a robot's arm. The design of the clamp may vary quite widely. In many cases, a set of interchangeable clamps is used, suited for various types of operations and shapes of objects. In addition to ordinary mechanical clamps, the clamps may be magnetic, vacuum-type, etc. Changing of clamps may be either manual or automatic.

In place of a clamp (or in the jaws of a clamp) some tool may be used: a nut driver, drill, knife, screw driver, welding head, brush, paint sprayer, glue applicator, marker, etc. Automatic or manual changing of tools and replacement of the clamp may be used.

Drive Systems

The actuating organs of the robot -- mechanical arms -- are objects of control in this system. A complex moving object, the movements of all elements of which must be controlled. This determines the jobs of the drive devices, each of which realizes controlled motion of a given joint of the arm by responding to signals formed in the control system.

The drive devices are placed in various ways to control the motion of the arm. As of now, they are generally placed directly at the joints or on the elements of the arm near a joint. This placement is suitable for low-power drives, i.e., when the load-lifting capacity of the arm is low. /37

At times, all drives are placed in a single motor unit on the body of the manipulator, near the shoulder joint. They require cable, gear rack or selsyn transmission of motion from the motor unit to the joints; this is preferable for more powerful drive units, since the elements of the arm then need not contain the drives.

It is easy to realize any kinematic system, to produce a higher efficiency with the first type of arrangement of the drives (due to the lack of long power transmitting systems), and the first method can achieve greater universality of attachment of the arm to the body. The second type simplifies the achievement of "comfort" for the drives themselves when the must operate under extremal conditions, lightens the elements of the arms, thus simplifying manipulation, although the total weight of the manipulator may increase.

A combined version of arrangement of drives is also used (some at the joints, some in the main body); this system allows a combination of the advantages of both types.

Various types of drives are used in robot manipulators: electric, hydraulic and pneumatic. An extensive literature is available on the problems of drives, and there is no need to study them in detail here. Let us simply briefly discuss the specific peculiarities of their use as the actuating devices for robot control systems.

DC electric motors are widely used. Their shortcoming is the presence of the commutator; otherwise, they are distinguished by their high operational reliability, good control properties when a broad range of regulation of speed is required with low power losses.

DC motors may have either independent or series excitation. In recent years, motors with series excitation have been more commonly used, with one or two (split) exciter windings. This type of motor has high starting torque, so that it better receives changes in the load force and has better reversing prop- /38
erties. These factors are very important for our purposes.

The speed of such motors can be controlled by means of an electric machine amplifier, magnetic amplifier or various electronic control circuits. Electronic circuits, incidently, are quite promising. They can be subdivided into linear and impulse types. In impulse circuits, transistors are used, operating in the switching mode, or thyristors (allowing the control of both low and high power motors). In particular, the appearance of thyristor control circuits has simplified and made more reliable the power unit using a split-winding motor with series excitation, emphasizing its advantages for use in robot manipulators.

Speaking of the controlled electric drive, we should immediately discuss the question of two inseparable parts, namely the reducer and correcting devices. The problem is that robot manipulators have very high requirements for drive compactness, efficiency, accuracy and dynamic qualities of motion over a broad range of speeds (including very low, "creeping" speeds), precise and reliable fixation of the position of the arm, etc. All of this has required the creation of a new type of electric drive consisting of a single compact module -- electric motor, reducer and correcting devices (at least internal feedback). Only when all parts of the drive are developed together and manufactured as a unit can the complex of requirements mentioned above be satisfied.

The reducer in such a model, with a high transfer ratio, must have minimum dimensions, as little friction and clearance as possible. The possibility must be provided of "building in" the module inside the hinge of the arm or on one element near the hinge (with minimum weight increase). Most promising for today are new types of reducers -- wave transmissions in various modifications, including so-called responsyns.

The dc electric motor in the control system of an arm may be replaced by an ac motor. However, this problem has been significantly less developed.

Another important element of the actuating device of a control system consists of the electromagnetic induction clutches. /39 Their advantages are simplicity of design and the fact that they allow a single electric motor to be used to control the motion of all the joints of an arm (each having its own clutch). Thus, a contactless drive system for the hinges is achieved, with significantly less inertia, low power consumption with great force, and excellent dynamic qualities of arm motion. We should also mention high reliability and durability of the operation of such clutches.

However, there are shortcomings in the design of actuating devices of this type, also related to the use of a single drive motor. First of all, the motor operates continually, i.e., there is constant power consumption, even when many of the joints of the arm are stationary. Secondly, failure of the motor causes the entire system to fail. Nevertheless, the advantages mentioned above frequently make this principle quite desirable when the robot must operate in a corrosive medium or when there is danger of an explosion.

Robot manipulators also use various types of stepping motors. This discrete control system allows higher accuracy of reproduction of the program of motions. Furthermore, stepping motors are promising in combination with the digital control machine. However, when they are used, particular concern must be exercised in the design of the correcting devices to achieve smoothness of motion of the clamp and of control dynamics. Therefore, the use of stepping motors requires the creation of special modules.

Let us now consider hydraulic drives. Piston drives (hydraulic power cylinders) and blade drives (hydraulic quadrants) are most frequently used in robot manipulators. The transmission of motion from the output shaft of the drive to the corresponding degree of mobility appears quite different than in the case of electric motors.

The hydraulic drive control device is usually electric (from which comes the term "electrohydraulic drive"). Of the various methods of control, the most popular at present is impulse control. The use of electrohydraulic drives with pulse-width control allows their reliability to be increased, while /40 expanding the range of change of conditions of operation and decreasing the cost of the control system.

In general, the favorable properties of hydraulic drives include: low weight per unit power, low inertia, high speed, possibility of producing a low speed of motion without the use of a reducer (for example when a power cylinder is used). They operate successfully in underwater work, and in industrial work, together with electric drive devices.

If great power is not required, the arms of the robot can be equipped with pneumatic drive with either electric or fluidic control and correcting devices.

Due to the specifics of the dynamic, accuracy and design requirements (same as for electric drives), hydraulic drives, as well as pneumatic drives, must be carefully developed, always in combination with the entire automatic control and correcting system.

It is difficult to solve the unusual problem of automatic distribution of the working fluid or air by means of special devices among all of the drives of the different degrees of mobility (which is particularly important when the robot utilizes an independent power supply). Here, the factor of limitation of the total power which can be used and which should be distributed considering all possible modes of joint operation of the mechanisms of the robot becomes particularly significant.

The factor of limitation of the total power with an independent power supply of the arm is just as significant for electric drives. Here also additional automatic devices are required, regulating the proper distribution of power among individual degrees of mobility of the arm with various levels of limitations for various joints.

Furthermore, we must also consider that the limited capability of an independent power supply may sometimes significantly influence the dynamic qualities of motion of the arm. The outlines of the working characteristics of the drives may be distorted, or they may shift (float). This is correct for all types of drive devices.

Partially in connection with this, but mainly due to the /41 need to minimize the dimensions of drive devices, increase efficiency to the maximum (achieve the minimum power consumption regardlessof power supply characteristics), the completeness of the power design of the drive units of an arm is of tremendous significance. It is complicated by considering possible mutual influences of all degrees of mobility.

We should also note the importance of studying the dynamics of a drive device as a tracking system for each degree of mobility. Considering all of the elevated requirements for dynamic and static properties of motion of individual elements of the arm, we can synthesize feedback (as to speed or position) and other correcting devices. In this case, we must consider the influence of nonlinearities, for example clearance and drive friction, as well as the elasticity of the mechanical drive. They are compensated by correcting devices, particularly those which are also nonlinear.

Thus, the dynamics of each drive must be worked out individually. However, as we shall see, this is far from sufficient, and is rather only the first, initial stage in the dynamic investigation of the motion of a robot arm. However, it is quite necessary as a basis for further work.

A new class of robot arm drives is made up of drives with directed action envelopes. These may vary quite widely in design, depending on the desired nature of motion and the required power. They may be quite sensitive, low power devices, as well as extremely strong, high power devices. They include bellows, tube and other designs.

Flexible directed action envelopes are reinforced so that when fluid or gas pressure acts upon them, they deform primarily in one predetermined direction. They must have high stability of elastic characteristics.

These envelopes, better than other types of drive devices, imitate the action of the muscles of the human arm. If, for example, we take a rubber tube reinforced with capron fibers along its length (parallel to its axis), when pressure is fed into the tube, it practically does not stretch in length, but rather "bulges" to the sides: its rigidly clamped ends are thus /42
forced to come closer together, so that the structure as a whole becomes shorter as it bulges (retaining the length of the bent sides).

If we attach the ends of such an envelope to two elements of an arm connected by a hinge (for example the elbow joint), as it contracts longitudinally the envelope forces the elbow joint to bend.

Bellows envelopes are given preference when high power is required.

One special problem is the development of new principles for miniaturized manipulator drives.

Means for Motion of Robots

Many practical applications of robot manipulators require that the body move through some medium. Here also, any of the existing methods of movement may be used, including walking, jumping and ordinary methods.

An industrial robot, as it moves over the floor of a shop, may use an ordinary rail track or a carriage which follows no track but is automatically or remotely controlled. Automatic control of the motion of a carriage may be combined in a single system with the control for the action of the arms of the robot. Then both systems are operated by a single programmer or computer in correspondence with a single plan of operation of the robot.

Another method of motion is installation of the robot on a support which moves on rollers across a floor or on a rail attached to a wall. Such a robot might be called a long-armed mechanical ape. Control of the motion of the support may also be included in a single control system with the control of the arms.

These types of motion are characteristically used for loading and unloading operations, storage and delivery of tools and materials to working locations of other robots which are stationary.

The wheels of the trucks are controlled in various ways. This might include a drive on the rear axle with steerable front wheels, or a drive unit controlling each wheel separately, which increases the maneuverability of the carriage. Finally, each wheel may be attached to a single support, with the plane of the wheels rotating around a vertical axis. Then, when the planes of all wheels are turned simultaneously by the same angle, /43 the carriage can move forward (without turning) on a straight line in any required direction from any point on the floor. There are also other versions.

If the drive is located separately in the hub of each wheel (so-called motor-wheels), the same electromechanical drive modules are used as are used to control the motion of the joints of the robot arm.

All of this is also true of the motion of construction and installation robots, when a smooth area or special rails is available. With uneven, loose, viscous or wet areas, tracks provide good mobility. However, wheeled carriages are also suitable for this type of terrain, as the Soviet lunokhods have confirmed. It is particularly important that each wheel be independently suspended and individually driven (i.e., motor-wheel).

The wheels may be made light, as of screen, allowing them to move over loose soil. If the wheels begin to spin (for example when climbing a slope), they may be made to "walk" with the wheels locked. It is sufficient to have but two joints (knee and hip) with a controlled drive. First, for example, the front left wheel is shifted forward and the entire carriage is pulled forward on one side; at the same time, the right rear wheel is shifted forward and the position of the carriage is thus straightened. Walking can also be organized in other ways. As soon as conditions are met, the carriage begins rolling again.

There is doubtless also interest in purely walking machines -- the latest word in this area. Walking mechanisms are made with 6, 4 and 2 legs. The greater the number of legs, the greater the version of gaits (a gait refers to a sequence of alternate movements of the legs). Different gaits have different capabilities as to speed and crc sing of obstacles.

It is most difficult to produce a machine which walks on two legs; this requires an unstable condition of the body as a whole and, in essence, consists of a series of controlled falls. It is not easy to provide dynamic stability of motion with this type of walking, although mechanisms of this type /44
are under development.

Special infestigations have been performed on four- and six-legged gaits. Each leg is a kinematic chain with two to four degrees of mobility. The maneuverability required is not as great as that of a robot arm; the legs have a fully predefined type of movement.

Therefore, each leg generally requires one drive with a fixed program of movement of all joints. Of course, individual drives can be placed at each joint with a predetermined program interrelating their movements; a change is made from one gait to another at the required moment by the program.

It is important to develop walking machines which automatically cross obstacles (rocks, holes, trenches) or avoid them. The mechanism must be able to recognize such obstacles itself. In the simplest case this is achieved by feeling with the leg. For example, if a leg bumps into an obstacle, it must be lifted higher (by a special program) and step further. If it encounters a hole, it must be stretched forward. If all capabilities are exhausted, the direction of motion must be changed (obstacle avoidance). Another method is examination of the profile by some type of radiation and automatic adjustment of the gait in response to this information.

We note that all surface carriers of robots (wheeled, tracked, walking or combined) can be controlled by widely different methods, both independently and by means of a human operator either located in the carrier itself or at any distance from it.

One interesting new method of moving a robot over broken terrain with vegetation, rivers, gullies or hills is jumping or short flights using light, compact reaction motors. The motors are attached to the body of the robot, can rotate, are easily switched on and off and provide for smooth landing.

Here also various types of terrain radar are used and the program of movement can be changed in response to the information thus generated. In contrast to this fully automatic mode, remote control from a control panel, stationary or mobile, is /45 possible, controlling the operation of the motors and of the robot itself.

Jumping is frequently combined with wheel motion. The suspension system of the wheels also acts as a shock absorber when the robot lands after a jump. A combination with other methods of motion is also possible, for example with floating across bodies of water, etc.

Incidently, speaking of water, the floor of the seas and oceans, special mobile controlled deep water vehicles are created for this environment, either unmanned or manned, with a crew of one to three persons. The actuating devices of the robot are located on the outside, the control apparatus on the inside. Control may be independent or remote from surface, underwater or shore locations. With independent control, communications, supply and hoisting lines, etc. are still necessary. However, fully independent robots are also possible.

Furthermore, deep water robots, for example for underwater construction and installation work, can move over predetermined areas of the bottom by "dry land" methods as well.

Robots for operations on the underwater portions of ships are equipped with the corresponding means of movement. If permissible, rails are used. Otherwise, the robots are suspended on lines with attachment to the outer surface of the hull where the work is to be performed.

A similar situation exists in the case of movement of the robots on the outer surfaces of spacecraft and orbital space stations, when stationary installation of the actuating portion of the robot outside the spacecraft is insufficient.

We can also, of course, think of mobile controlled apparatus similar to deep water apparatus to carry robots in space, in the air or in the atmosphere of another planet (flying controlled robots).

As concerns the movement of robots over the surfaces of the moon and the planets, everything which we said earlier concerning terrestrial surface movements over uneven and broken terrain applies here as well, but we must also consider the specifics of the lunar or planetary conditions.

CONTROL AND SENSING SYSTEMS

Principles of Design of Robot Manipulator Control Systems

At the begining of our little book, we described robot /46
manipulators which differed basically as to the principle of design of the control and sensing systems. A general functional diagram of a control system was presented, showing that they differ in the presence or absence of various boxes in the overall plan and in the composition of the hardware represented by each box.

A control system has a hierarchical structure (Figure 7). The first, lowest level consists of the elements controlling the direct motion of the links in the arm: these are the drive devices with their feedback units and correcting mechanisms. Receiving signals from the devices in the next, second level, they transform them into action, mechanical motion, i.e., they operate as automatic tracking systems.

The control signals are formed at the second level of the control system of the robot manipulator. Its most important task is expedient distribution of control signals among all the hinges of the arm in order to perform the required movement of the clamp in space to perform some elementary operation. This includes selection of a trajectory, if necessary bypassing obstacles and with optimization of the controlled process of movement of the arm on the basis of some criteria.

This second level of the control system is realized in different ways: by means of a programming device, computer or assigning arms. The latter are used in copying manipulators. The programming device is used in most modern industrial robots. However, all three methods or any two of them may be combined in a single system. We discussed the purpose of these systems at the beginning of the book.

At the third control level is the overall task of the operation. here its details are developed, i.e., it is broken down into a sequence of elementary movements of the clamp in correspondence with a certain set of rules, which are generally realized by a computer, in which the rules are stored in some form.

Suppose, for example, the third level of the control system of the robot has received an assignment -- using a nut driver,
tighten a nut which holds down some part in an assembly process. /48
Let us assume that the nut and nut driver are located in positions set aside for them. The operation is broken down into elements: move the arm from its initial position to the location

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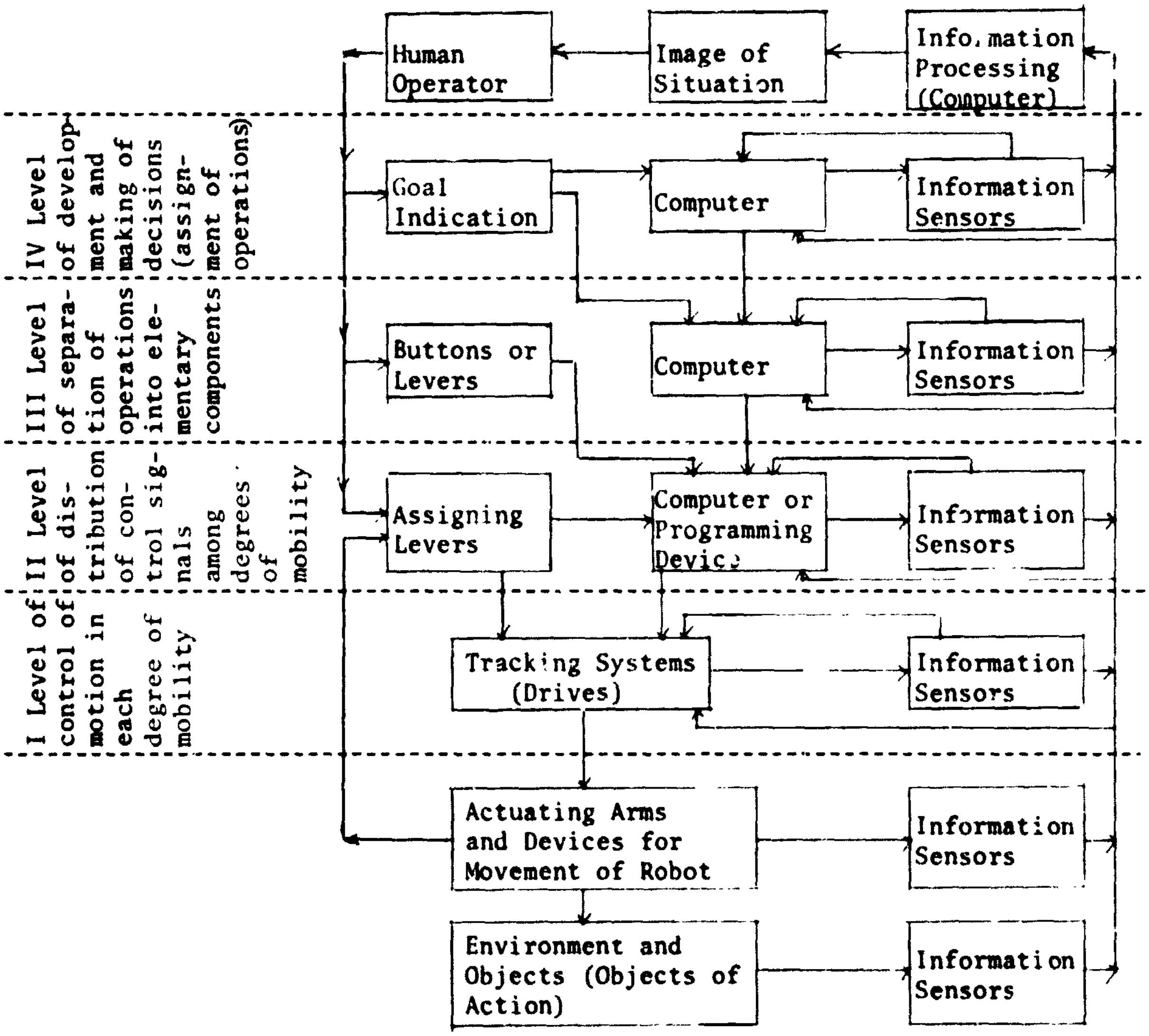

Figure 7. Hierarchical Structure of a Robot Control System

of the nut driver, automatically attach it to the arm, move the arm to the location of the nut, grasp a nut in the nut driver, move the arm to the point of assembly, place the nut on the end of the bolt (or lug), screw on the nut. This breakdown of operations into elements may be even more detailed.

The signal indicating the need to perform each element of the operation is supplied by the third level of the control system to the second level. There, signals are sent out to all degrees of mobility of the robot arm in order to perform the operation in all its elements.

At the third level of the control system, generally speaking, operations of a significantly larger scale than the example we have just discussed maybe stored. The entire assembly of a complex unit or machine, a certain complex of construction and installation work, complex operations under extreme conditions (underwater, in space, with radiation), etc.

In systems with button and lever command control, the human operator is located at the third level, pressing the buttons or moving the control lever: the operator thus breaks down a large operation into its elements. A computer or simpler computation device and automation equipment distribute the signals among the degrees of mobility.

The highest, fourth level of the control system of the robot is necessary when information is not received in advance as to which operation will be required. The robot, based on the surrounding unknown and changing situation, must itself decide which operation is needed under the conditions at hand. Consequently, the fourth level is the level of decision making concerning the need to perform in a given operation under conditions not defined in advance (elements of artificial intellect). The decision made is transmitted to the third level of the control system and then down through the system for realization.

Whereas the fourth level requires "creative" activity of the computer, the third and second levels can frequently be deterministic and use, for example, a programming device. As /49
concerns the computer, it may be a single machine, but it is preferable to have a separate machine at each level. Many computers are quite promising for this purpose.

Each level of the control system of the robot has feedback links, through which information is transmitted on the status and actions of the lower levels, as well as internal feedback (see Figure 7). These links consist of the required information sensors and devices for information processing (with conversion to the required type for functioning of the given level).

The system of sensors and feedback links will be described. At this point, we need only say that at the lower levels it is quite simple, while at the upper levels it is rather complex. This is related to the need for artificial vision, recognition of patterns and elements of artificial intellect.

As concerns the human operator, he can participate directly in the processes of control through the second or third level, as is shown in Figure 7. However, he may also participate only in preliminary adjustment or programming of the operations to be performed, working through these same two levels, then perhaps later interfere in the operation of the highest levels, in the stages of decision making and assigning of operations on the large scale (by means of various goal indication methods). The last method of participation of man is called "the supervisory mode of control by the human operator."

In this case, the operator should have before his eyes an image of the situation at the point of action of the arms of the robot and a clear representation of the other necessary information on the functioning of all elements in the control system and actuating organs.

Planning of the control system of a robot manipulator has many peculiarities. Some of these were noted in our description of the actuating organs and drive devices. At that point we formulated the requirements for the control of motion of the arms. The control system must be created in accordance with these requirements.

First of all, for its planning, as always, we must have the equation of the dynamics of the controlled object. In this case, the object of control is the artificial mechanical arm, a complex mechanism, the elements of which are connected in series /50
by rotary hinges or devices allowing telescopic motion.

The equations of dynamics of the three-dimensional motion of the arm mechanism are quite complex. Actually, the instantaneous position of the end point of each element in space is determined by three coordinates relative to its initial point. This point, in turn, the end point of the preceding link, is determined by three instantaneous coordinates relative to its initial point, etc. A series of interconnected differential equations with complex nonlinear kinematic relationships and with variable moments of inertia depending on the nature of the motion is produced.

Furthermore, one must consider the equation of the dynamics of the drives for each hinge, as well as the influence of the elasticity of certain mechanical couplings.

Obviously, analysis of the process of control, and particularly synthesis of a control system for such an object, represent very complex tasks. Only machine methods of planning using rather large computers are applicable. A full mathematical model of the dynamics of the object of control must be produced, a model which can be conveniently realized by a computer.

Due to the great complexity of the full equations of the dynamics of the three-dimensional motion of the arms of a robot as objects of control, it is not expedient to solve the entire problem using the full equations. It is better sequentially to develop the control system by units, beginning with the lowest level, working individually for each degree of mobility.

Initial synthesis of a tracking system for each degree of mobility taken individually is performed in the lineal plan. The synthesis of correcting devices provides the required accuracy and smoothness of controlled movements and the corresponding quality of transient processes. The nonlinearities are then considered and the correction is refined and perhaps replaced by a nonlinear correction. The nonlinearity results not only from the internal properties of the drives of the arm, but also from its operating modes, for example with an elastic /51
support on some object.

The next stage is development of tracking systems considering the mutual influence of degrees of mobility, first in the linear plan, then considering the unavoidable nonlinearity, and perhaps with a nonlinear correcting device. Additional correcting couplings may also appear here between the degrees of mobility (to eliminate undesirable effects of their mutual influence). Consideration of all factors is important also because the mutual influence of degrees of mobility of the arm on each other most frequently worsen stability and quality of the transient processes in comparison to each tracking system taken individually.

The system produced can then be "played" with the full model of the dynamics of the arm of the robot on the computer or on an analog-digital complex, possibly also with actual attachment of the interconnected tracking systems. Everything together makes up a model of the lower (first) level of the control system. This model becomes a reliable basis for subsequent planning of all of the upper levels.

The planning of the upper levels, beginning with the second level, differs significantly from what we have described for the lower level. The basis of planning here is solution of problems of information nature, which are assigned to a computer or a programmer, but considering the properties of the dynamic object and its lower control level. This lower level acts as a terminal for the computer, a terminal with special dynamic characteristics.

In planning the upper levels, many cybernetic problems arise, related to the development of the best languages for representation of information, for reception, processing and outputting of information, for development of the logic of functioning of large numbers of interconnected units, etc. These also include complex problems of pattern recognition and development of solutions in accordance with the problems at hand (goal indication in some form) and the developing factual situation at the point of action of the arm of the robot.

A number of specific problems are related to consideration of the properties of the human operator as a link in the control system, which will be studied below.

We note, finally, that in the area of construction of such control systems of robots, certain particular problems have /52 been solved, but most problems are still far from practical realization -- representing a rich, broad area for activity in the scientific and practical aspects.

Basic Principles of Sensing of Robot Manipulators

The sensing or feeling of a robot manipulator is one of the most important factors of functioning of the control system. Sensing means installation of the corresponding information sensors, acting as sense organs. They are the sources of feedback for the control system. The information provided by the sensors must be transformed (processed).

Actually, the sensing devices in principle act as do the measuring or sensing elements in any automatic control systems. However, due to the specific features of their use, they are more complex and similar to the sense organs of man, and require the solution of a number of independent cybernetic (information) and engineering problems in their design.

The sensors output information on the condition and changes of the environment in which the robot arm operates, on the location and movement of objects of action, on the position and movement of the clamp and elements of the arm, and also on the condition and actions of all levels of the control system itself.

Tactile sensors are installed directly on the clamps of the actuating arm, i.e., sensing elements which react to contact between the clamp and any object. Contact may occur over only a small portion of the jaws of the clamp or outside the clamp. This requires that a number of tactile sensors be installed over the entire inner and outer surface of the clamp.

Furthermore, the same type of sensors must be installed in other areas on the actuating arm of the robot, for example at the extreme points of joints with which the arm might touch and obstacle or limitation of its working space. A timely signal and the corresponding reaction to it allows possible breakage or deformation to be avoided.

Tactile sensors are based on various principles, for example using known sensing elements from instruments used to measure small contact pressures. The information output from them may /53 also vary both in its physical principle and functionally. For example, the sensor may only note the fact of contact, or may also measure the contact pressure if necessary.

Signals from tactile sensors are used to provide feedback generally for the second level (see Figure 7), which controls the distribution of control signals among all degrees of mobility. At the second level (without participation of upper levels) the corresponding changes in the process of motion of the arm are developed. However, signals from the tactile sensors may also be used at higher control levels, in general planning and distribution of operations.

Other information sensors, for example small radar units, are installed on actuating arms as well, signalling the approach of the clamp or some other portion of the arm (or carriage) toward objects or obstacles within the limits of certain ranges. Here once again the signal may simply indicate that a given distance remains to the object, or may perform continuous or discrete measurement of the instantaneous distance or approach rate.

The signals from radar sensors also provide feedback to the control system. Due to this feedback, the program of motion in determining the distance to the object may be simply changed, or the rate of approach may be regulated, etc. Feedback is used at the second and higher level of the control system.

However, even at the first level, i.e., within the elements of the system itself (drive units), there is feedback from the elements of the arm to these drive units. This feedback is schematically shown in Figure 7 on the right. We will not analyze it, it is obvious from the figure (specific here is the feedback from the actuating arm of the robot to the assigning levers -- left portion of Figure 7. However, since it is related to the activity of the human operator, we will analyze it below.)

The information sensors may be of more special purpose, recording various properties of the environment and objects

(objects of action): temperature, radiation, illumination, sound, pressure, composition of gas or liquid, density, nature of the surface, etc. These sensors must frequently transmit information on the environment in which the robot operates to the command or observation post. However, this information may also be used at higher levels in the control system of the robot as feedback or initial information for automatic decision making concerning the performance of one operation or another. /54

In the last case, problems of artificial vision and pattern recognition become particularly significant. Artificial vision allows automatic creation of a model of the environment and the object in it at the highest level of control, with determination of the relative position and movement of the actuating arms among the objects in the environment. It becomes possible to organize automatic decision making concerning the performance of operations, with development of detail at lower levels. This type of sensing involves the creation of elements of artificial intellect: only the simplest particular cases have been solved to date in this area.

Artificial vision with pattern recognition can be based on widely varied principles: from optical (beginning with simple photosensors and scanning beams, ordinary or laser beams) to television and holography in any areas of the spectrum, including the infrared, as well as radar, sonar, other types of radiation, etc.

Automatic pattern recognition requires heavy loading of the computer, since it is quite important here to utilize characteristics and methods to yield a concept of the environment and the objects in it of minimum volume, involving only the most important points, without excess detail. Attempts are being undertaken in this direction and simple experimental models have been produced.

Bioengineering Problems of Control

We can speak of such problems when a human operator plays a significant role in the robot manipulator.

In the left portion of the general diagram of Figure 7, we show that the human operator can, first of all, directly perform all motor operations by means of assigning mechanical arms. He can control the motion of the arms of the robot by pressing on /55 buttons or a control lever, with a computer developing the corresponding control signals for the tracking systems of the actuating arms. Or, he may interfere from time to time (giving orders), with the necessary operations developed and performed by the computer each time.

We have discussed the direct participation of man in the processes of control of the actions of a robot manipulator. In addition to this, the assigning arms or buttons or levers may be used only for preliminary assignment and recording of the program of operations of the robot, after which it automatically repeats the thus programmed operations as many times as necessary (see second level on Figure 7). We are interested in this section in the first case: the operator in some way participates in the process of control of the actions of the robot.

The first mode is control of the actions of the actuating arm by means of an assigning organ similar to it (in a scale convenient for man). Such a system is called a copying manipulator. Its diagram is presented in Figure 8.

The operator manipulates the assigning organ, thus developing signals which control the tracking system of the actuating arms, distributed among the degrees of mobility. In other words, the drive of each degree of mobility of the actuating arm copies the motion of the same degree of mobility of the assigning organ.

In addition to the ordinary feedback of the tracking systems, it is particularly necessary here to provide visual feedback, which in the case of sufficiently great distances between operator and manipulator is realized by three-dimensional television. Ordinary television is also used, but it is significantly more difficult to work with it, since the operator then cannot distinguish depth of the image on the screen and may make errors. With short distances, direct visual observation or observation by means of simple optical devices is possible.

In addition to visual feedback, feedback of forces and moments arising in the actuating arm during performance of the operations is also provided. Transmitted to the assigning organ, they are felt by the arms of the operator. This reflection of forces is an important factor in increasing the effec- /57
tiveness of all the actions of the human operator. Actually, the nature of his actions is similar to that which would occur if he were working directly with the objects manipulated by the actuating arm.

There are various methods of passive and active reflection of forces (i.e., transmission of forces from the actuating arm to the assigning arm). In the active method the control system of the copying manipulator is called a two-way system.

Passive reflection of forces consists in the following. On the actuating shaft of each element of the manipulator arm a torque sensor is installed, the signal from which is transmitted to a so-called passive loading device on the shaft of the assigning organ. This is a clutch which causes the operator to feel resistance to the movement of the assigning shaft. The amount of resistance is proportional to the torque (measured by the sensor) on the actuating shaft. Data from the torque sensor are transmitted to the passive loading device in the form of an electric signal.

One shortcoming of the passive force reflector is that the operator feels the influence of the torque on the actuating shaft only when he moves the shaft. When he stops moving the assigning shaft, he stops feeling the force.

Active reflection is achieved by means of a two-way tracking system, i.e., a tracking system which transmits mechanical effort both from the operator to the actuating arm and in the reverse direction. There are two types of such systems: symmetrical and asymmetrical.

A symmetrical two-way system consists of two tracking systems (Figure 9). The right system controls the load shaft (I, M), i.e., the shaft of the actuating arm of the manipulator. It consists of an amplifier (>), control system CY and motor D with rotating torque M and moment of inertia I. The same sort of tracking system is shown on the left. It controls the position of the operator shaft, i.e., the shaft of the assigning arm of the manipulator (I_{op}, M_{op}). PS show the position sensors, SS the speed sensors. The scales of the system may differ.

The two systems, as shown on the figure, are interconnected and closed as to position. The system is two-dimensional, since /59
any coordinate α may be an input quantity, and the actions of the two systems cannot be independent. The distinguishing feature of a two-dimensional combination is that, in addition to tracking position, it also transmits forces in both directions, the primary purpose in this case.

Let us now look at an asymmetrical two-way system (Figure 10). This includes an actuating tracking system (right), which controls the position of the load shaft, and a moment loading device (left), which transmits to the operator the value of the loading moment from the actuating shaft of the manipulator arm (DM = moment sensor).

The tracking system of the actuating shaft is the same as in the preceding case. The loader here is closed as to moment, the input receiving a quantity proportional to the moment on the actuating shaft. Other types of moment loaders are also possible.

Of course, simple copying manipulators are used without force feedback. However, it is more difficult for a human

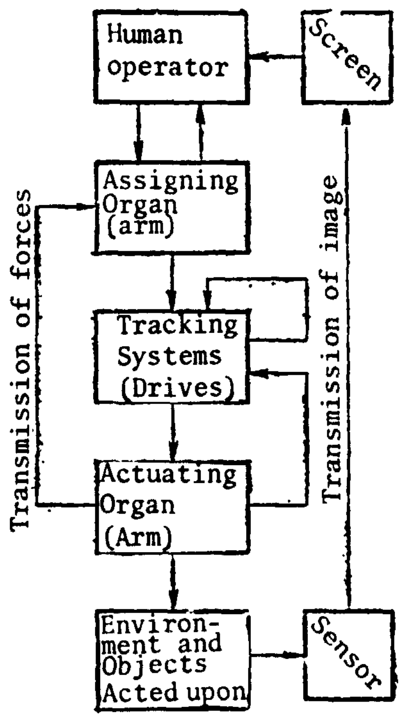

Figure 8. Diagram of the Copying Control Mode

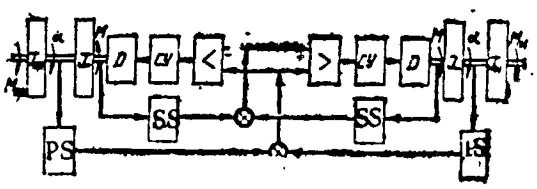

Figure 9. Asymmetrical Two-Way System

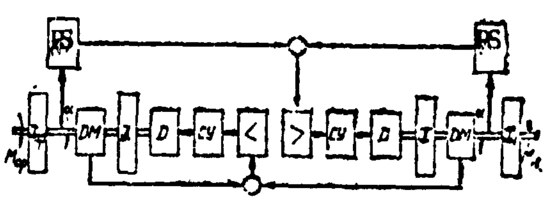

Figure 10. Symmetrical Two-Way System

operator to work with such systems, requiring more effort; all operations are performed much more slowly. /56

There is interest in the control of robot manipulators by means of levers. Two versions are possible: speed control and force control.

In the first case, the operator, as he presses on the control lever, assigns the desired speed vector of motion of the clamp of the actuating arm of the manipulator. The direction of clamping is assigned by the direction of the velocity vector, while the clamping force (and therefore the degree of displacement of the spring-loaded lever) is assigned by the magnitude /58 of the vector. These parameters are transmitted to a computer or special calculator. The parameters are analyzed and the control signals are formulated and fed t each hinge of the actuating arm of the robot so that the clamp actually moves at the required velocity in the required direction.

The control arm has a convenient shape. It allows slight spring-resisted movement either in all six possible directions in which the clamp can move in space, or in three directions. In th s case, two levers may be used: one for advanc- /60 ing and retarding motion of the clamp, the other for angular orientation of the clamp in space.

Another type of organization of control of the motion of the clamp by means of levers -- control by force -- consists in the following. By pressing in a certain direction with a certain force on the control lever, the operator assigns the desired motion not directly, as in the first case, but rather indirectly, through force factors. Mainly, the magnitude and direction of the force is transmitted to the computer (or special calculator). There the control signals for each motor at the hinges of the actuating arm are generated, so that the clamp moves as if it had been pressed with the same force (magnitude and direction) which was applied to the lever.

In both cases, in addition to sensations of force on the control lever, the operator has visual feedback (either direct or by means of television).

With any participation of a human operator in the control, study of his behavior during the process and creation of the optimal conditions for "combining" the man with the automatic machine at the "input" and "output" are very important. In the last case, the human operator is considered an element in the overall control system.

At the input of the operator, the initial visual information on the condition of the environment, position and movement of the actuating arm of the robot manipulator is presented clearly. This is done by a television screen and other information devices. At the output are either devices for goal indication, or buttons or levers, or assigning arms. In the last case, the devices reflecting the forces should be considered sources of additional input information, along with the visual information.

In order to achieve the maximum possible effect of the actions of the human operator in each type of system, his behavior in various control modes, with various principles of design and combinations of parameters of input and output devices must be studied. Each of the three basically different cases of participation of man in the process of control indicated at the beginning of this section requires a specific approach.

The greatest degree of "connection" of the human operator in the process of control of the actions of the actuating organ of the robot occurs in the copying mode. In this case, in addition to all the psychophysiological problems of studying the behavior of the operator which are encountered in any man-machine system, one must also study the joint motor functions of the arm of the human operator and the assigning organ of the manipulator. /61

The arm of the human operator may be connected to the assigning organ (in the form of an artificial mechanical arm) in various ways. Let us note three versions. The first is when the assigning organ of the manipulator is attached to the lower portion of the human arm; all movements of the hand are fully tracked. The upper elements of the assigning organ move in their joints without attachment to the arm of the operator. This is the commonest version. It allows, first of all, rather definite assignment of the motion of the hinges of the assigning organ and, through it, of the actuating arm of the robot, while placing minimum restrictions on the movement of the operators arm and thus providing operating comfort.

The second version is a stronger connection of the human arm to the assigning organ, including attachment of the forearm and elbow joint. The selection of this version is based on conditions of maneuverability of the actuating organ. Finally, the third version is when the elements of the assigning organ are not attached to the operators arm. He simply grasps the end of the assigning organ in his hand and moves it in the required direction.

Planning of such control systems requires careful preliminary experimentation with various operators and models of manipulators using analog or digital computers. A significant role here is played by the dynamic (inertial, oscillating, etc.) properties of the actuating organs of the manipulator in various modes of functioning. Full mathematical modeling of the problem is possible if a mathematical model of the motor functions of the human arm can be developed with the sensations of force and visual observation of the results of movement of the actuating arm of the manipulator.

Both versions of modeling (partial and full) involve many bioengineering problems in combination with problems of /62 physiology and psychology. In addition to the dynamic properties of the actuating organs already mentioned ("at the output" so to speak), it is important to consider the perception of the input information by the operator, on the basis of which he draws conclusions concerning his future control efforts. The scale of the television image, its clarity and the form of representation of all other information are also important here.

In the case of long communication lines, separating the control point and the point of action of the robot (for example between the Earth and the moon), the delay involved in transmission of the control signals and return of television signals becomes important. The actions of the human operator are significantly complicated. There are methods of compensation for the undesirable influence of the time lag on the stability and quality of the control process.

Furthermore, we must consider many of the specific difficulties of functioning of human operators when the robot functions in various extreme conditions. For example, there may not be sufficient space in a deep water apparatus to place the assigning organ as would be desired and provide sufficient working space (the actuating organ is outside the apparatus). In this case, we should thing of replacing the assigning arm with a compact control lever. However, we must recall that in this case as well a special computer will be required to distribute the control signals among the degrees of mobility of the actuating arm.

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In conclusion we should note that robot manipulators are a very promising new technical device which can provide basically new qualities for modern complex automation systems in production shops, in warehouses and supplementary services, and in all other spheres of the economy in the operation of various types of equipment, including the exploration of underwater and outer space, in transportation, construction, medicine and other areas.

Robot manipulators can help solve an important social problem in the sense that they liberate man from monotonous untrained manual labor, replacing him in dangerous areas and in areas where man's presence is impossible. /63

However, the creation of robot manipulators is a complex and interesting problem, including many problems of mechanics, automation, cybernetics and bionics which have not yet been solved as applicable to this area of technology.

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